On Service Time Estimation in 802.11 WLANs with Heterogeneous Traffic Sources

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Abstract—This work presents a simple method to estimate IEEE 802.11 Distributed Coordination Function (DCF) service time. This is the total amount of time needed to transmit a given frame, which is defined as the duration from the instant a node starts the transmission, until the instant when the transmission task effectively finishes. We are motivated by the fact that IEEE 802.11 DCF does not provide time-bounded transmissions. Thus, it is important to have an estimate of the service time because most of the times a physical connection between two nodes exists, but it is misinterpreted by the upper layers due to the long waiting time to obtain a response from a node. In this case, the estimate of the service time can be used by the upper layer protocols to solve some problems caused by IEEE 802.11, such as routing failures due to timeouts or even TCP connection failures.

The congestion time in IEEE 802.11 before each (re)transmission, which is due to the random access mechanism employed in the CSMA/CA, makes it more difficult for service time to be estimated. Our approach needs only local information available at each node and considers a realistic scenario where the traffic sources may have different data generation rates (heterogeneous traffic). The applied methodology is described and we present simulation results to assess its accuracy.

I. INTRODUCTION

The IEEE 802.11 protocol defines the medium access control (MAC) for wireless local area networks (WLANs), specifying the physical and logical layer. The standard [1] defines two operation modes: Distributed Coordination Function (DCF), used for asynchronous data transmission and the Point Coordination Function (PCF) that needs a infrastructure to provide collision free and time-bounded transmissions. This work focuses on the DCF mode, which uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. DCF does not require a fixed network infrastructure, and thus it is suitable for Mobile Ad Hoc Networks (MANETs). However, due to the distributed nature of the protocol, time-bounded transmissions are not guaranteed. This fact poses significant challenges the interaction between 802.11-based networks and well-established upper layer protocols such as TCP or several routing architectures [2].

A lot of effort has been devoted to describing the performance of the IEEE 802.11 DCF (see [3] to [6]). Several models are available for describing the IEEE 802.11 protocol. The expected duration of time from the moment a node decides to transmit a frame until the instant when the frame is effectively transmitted, is one of the outputs given by these models. This time interval, called service time, represents the total amount of time needed to transmit (serve) one frame. However, most of them assume that each node is generating traffic homogeneously (using the same traffic generating rate for all sources), as in [4]. More recently, the works [5] and [6] analyze the 802.11 protocol assuming non-saturated and heterogeneous traffic conditions. The model described in [5] is based on a Markov chain and considers the case when there are two distinct frame arrival rates in the network. This is what we refer to as heterogeneous traffic. The average waiting time per frame is derived. But when more than two frame arrival rates are considered, the complexity of the Markov chain increases, which makes this methodology unscalable. The model presented in [6] is based on the Markov chain [3]. The authors consider non-saturated heterogeneous traffic sources, assuming different Poissonian traffic generation rates for different users. Assuming infinite MAC buffers, the average MAC delay is derived by applying a M/G/1 queuing model. This approximation is more scalable than the proposal in [5].

The works in [4] to [6] present IEEE 802.11 models where the frame arrival rate for each node is known, but they do not address how to use the models when this knowledge is not available, as is the case when a node wants to estimate the protocol behavior in real-time. The works in [8] and [9] focus on IEEE 802.11 estimates of unknown parameters. [8] presents a maximum-likelihood estimator to measure the IEEE 802.11 channel’s quality. The simulated results show that a simple maximum-likelihood estimator based on local sampling (without message passing) can accurately estimate the proportions of frame losses arising from collisions and from other losses (channel errors).[9] analyzes how to estimate the number of competing terminals communicating in a IEEE 802.11
saturated network. The work compares the estimates given by a Auto Regressive Moving Average (ARMA) estimator and a Kalman filter, both derived from the model presented in [3].

This work presents a methodology to estimate the IEEE 802.11 service time that relies on information about the MAC transmission buffer occupation and the channel activity. We are motivated by the fact that IEEE 802.11 DCF does not provides time-bounded transmissions. This poses new challenges for upper layer, since an existing physical connection between two nodes is often misinterpreted by upper layers due to the long waiting time to obtain a response from a node [2]. Hence, an estimate of service time can be used by upper layer protocols to solve some of the shortcomings of IEEE 802.11. These problems are due to the misinterpretation of existing physical links between nodes, that cause erroneous decisions at upper layers, such as routing failures due to timeouts or TCP connection failures [7].

Service time estimation in the IEEE 802.11 protocol was studied in [10], for saturated and traffic-homogeneous networks. The work [10] shows that the service time distribution can be approximated by a geometric distribution. Using an M/Geo/1 queueing model (“Geo” refers to a geometric distribution), the authors validate their method by obtaining accurate results when the network is operating near saturation. The authors of [11] also propose a distribution for the service time as a function of collision probability observed in the channel, showing that it is exponentially distributed. The authors apply M/G/1 and G/G/1 queueing models to study the MAC delay for both saturated and non-saturated cases, but only for homogeneous traffic. Aiming for real-time deployment, we assume that traffic sources (nodes) can be either saturated or non-saturated and that each of them has a given traffic generation data rate, which can be different from the others’ (we assume heterogeneous traffic). In this work, we present a simple but effective (in terms of accuracy and computational power) methodology to estimate service time in real-time for heterogeneous traffic (heterogeneous traffic is a particular case of heterogeneous).

The rest of the paper is organized as follows. In Section II we define the service time for IEEE 802.11 protocol. In Section III we present the methodology to estimate service time. Experimental results obtained through simulations are given in section IV and finally, some concluding remarks are given in section V.

II. IEEE 802.11 SERVICE TIME

One of the solutions to allow multiple nodes accessing a shared channel is to apply channel access probabilities to each node (p-persistent access). IEEE 802.11 uses the well known CSMA/CA scheme. When a node has a frame to transmit it starts by determining if the channel is idle during a fixed period of time (DIFS time interval). If the channel remains idle during the DIFS period, a node copies the frame to the channel and the contention time is only the DIFS period wasted to monitor channel activity. If the medium is found busy, the transmission will not happen immediately and a node starts the binary exponential backoff (BEB) mechanism (we denote this situation as prep backoff). The BEB starts its counter with a randomly chosen value between zero and the maximum backoff window size used in the present backoff stage. The transmission only occurs when the backoff counter expires (reaching the value zero). Thus, if the BEB counter is initialized with a value larger than zero, it will be decremented until it expires. After every transmission, the backoff algorithm is performed (we denote this situation as post backoff) to ensure that frames transmitted from one station are not sent from head to tail without some separating interval. So, if another frame is ready for transmission before this post backoff period ends, the station has to execute it until the end before transmitting the frame.

Each time unit of the BEB counter represents an amount of contention time (we name it slot) for the channel which is a function of channel occupancy. IEEE 802.11 defines a fixed value (σ) for the duration of each time slot, which is the time unit used to define all timing values used by the protocol. If the channel is found idle during σ, each BEB counter unit matches the duration σ. But because the uplink and the downlink share the same channel, a node can receive frames from other nodes while the BEB counter is decremented. When this occurs, the backoff counter will freeze because the channel is sensed busy and thus, the slot will be larger than σ. Thus, time slots can be classified as:

- idle slots - if a node senses the channel idle for the σ time interval;
- busy slots - if a node senses one transmission (through the reception of a RTS frame or the reception of a data frame when the RTS/CTS mode or the basic mode is respectively used).

For busy slots the BEB counter is frozen until the channel becomes idle again. The busy slots can have duration Γs or Γc depending on whether the sensed transmission is successful or not, respectively, and they are given by

\[
\begin{align*}
\Gamma_s &= \begin{cases} 
E[p] + SIFS + 2δ + ACK + DIFS & \text{basic mode} \\
RTS + E[p] + CTS + 3SIFS + ACK + 4δ + DIFS & \text{RTS mode}
\end{cases} \\
\Gamma_c &= \begin{cases} 
E[p] + EIFS + δ & \text{basic mode} \\
RTS + EIFS & \text{RTS mode}
\end{cases}
\end{align*}
\]

where δ is the propagation delay, E[p] is the expected duration of the frame (which include headers and depends on frame’s size and the data transmission rate). All the remaining parameters are defined as in [1]. Fig. 1 illustrates a hypothetical scenario for channel activity.

Consider a network where a node j has a set of neighbor nodes \( N = \{1, 2, ..., n\} \) and define \( \tau_j \) as the probability that

\[
\begin{align*}
\text{CD} \quad \text{CD} \quad \text{CD} \quad \text{CD} \quad \Gamma_s \quad \text{CD} \quad \text{CD} \quad \Gamma_c \quad \text{CD} \quad \Gamma_s \quad \text{CD} \quad \Gamma_c \quad \text{CD} \quad \Gamma_s \quad \text{CD} \quad \Gamma_c \quad \Gamma_s \quad \text{CD} \quad \Gamma_c
\end{align*}
\]

Fig. 1. Different types of slots - idle slots (σ) when the channel is idle or busy slots when successful (Γs) or unsuccessful (Γc) transmissions are sensed.
node \( j \) starts transmitting in a given slot. For heterogeneous traffic sources, we can have \( \tau_a \neq \tau_b, a, b \in N \). The probability that node \( j \) senses the channel idle during \( \sigma \) is related to the probability that no neighbors access the channel:

\[
p'_{i} = \prod_{k \in N} (1 - \tau_k).
\]

Node \( j \) senses a successful transmission from its neighbor node \( u \) if \( u \) is the unique node accessing the channel (simultaneous transmissions cause collisions) and no channel errors occur during transmission. Denoting by \( p'_b \) the probability of occurring transmission errors (other than collisions) when a neighbor node \( u \) is transmitting, and assuming independence between each channel access and the event of occurring transmission errors, the probabilities that node \( j \) senses a successful or unsuccessful busy slot, are respectively given by

\[
p'_s = \sum_{u=1}^{n} \tau_u (1 - p'_b) \prod_{k \in N \setminus \{u\}} (1 - \tau_k) \tag{4}
\]

and

\[
p'_u = 1 - p'_s - p'_b. \tag{5}
\]

The expected duration of each backoff slot sensed by node \( j (T'_j) \), is defined using (1), (2), (3), (4) and (5):

\[
T'_j = \sigma p'_t + \Gamma_s p'_s + \Gamma_c p'_c.
\]

Thus, the average contention for each backoff stage \( k \) is:

\[
T_C(k) = \frac{W_k - 1}{2} T'_j, \tag{7}
\]

where \( W_k \) is the maximum size of the backoff window applied in the backoff stage \( k \in \{0, 1, ..., m\} \).

Each frame transmission can start in different logical states of 802.11 protocol and the average service time for each of these states is differently characterized. The different logical states fall within the following three cases (detailed in [4]):

- when the channel is found idle for the initial DIFS time:

\[
T_1 = (1 - p'_t) \left[ T_C(0) + \Gamma_s + \sum_{k=1}^{m} (1 - (p'_t)^k)(T_C(k) + \Gamma_C) \right] + p'_t \Gamma_s. \tag{8}
\]

- when the channel is found busy for the initial DIFS time:

\[
T_2 = T_C(0) + \Gamma_s + \sum_{k=1}^{m} (1 - (p'_t)^k)(T_C(k) + \Gamma_C). \tag{9}
\]

- when a frame is ready for transmission \( l \) slots before the post backoff period ends:

\[
T_3 = lT'_j + \Gamma_s + \sum_{k=1}^{m} (1 - (p'_t)^k)(T_C(k) + \Gamma_C), \tag{10}
\]

where \( m \) represents the maximum number of backoff stages. Finally, the expected service time is expressed by

\[
T = p_\emptyset [p_\psi T_1 + (1 - p_\psi)T_2 + (1 - p_\emptyset)p_\psi T_3], \tag{11}
\]

where \( p_\emptyset \) is the probability of having the served MAC queue empty and \( p_\psi \) is the probability of finding the channel idle during the DIFS time.

### III. SERVICE TIME ESTIMATION

We now present a technique to estimate the long term service time. We start by noticing that \( p'_t, p'_s \) and \( p'_u \), which are respectively given by (3), (4) and (5), can be computed in real-time for each node without requiring any change in the 802.11 protocol and all information required to compute it can be obtained from the IEEE 802.11 device driver. Let a node \( j \) be sensing the channel for the last \( B \) slots and let \( I, S \) and \( C \) be the sets of sensed idle slots, busy slots with successful transmissions and busy slots with unsuccessful transmissions, respectively. Then, \( p'_t, p'_s \) and \( p'_u \) can be estimated through the following relative frequencies

\[
p'_t = \frac{|I|}{B}, p'_s = \frac{|S|}{B}, p'_u = \frac{|C|}{B}, \tag{12}
\]

where \( |S| \) denotes the cardinality of the set \( S \). Note that the computation of estimates in (12) are also the basis of estimators presented in [8] and [9].

Having \( p'_t, p'_s \) and \( p'_u \), knowing the probability of having its transmission queue empty (\( p_\emptyset \)), a node can estimate the MAC service time by directly applying (11). But in real-time operation we must be aware of variable slot duration, which is given by \( \sigma \) when the channel is busy and by the approximated value \( \Gamma tx = \Gamma_s - DIFS \) when a transmission occurs\(^1\). Hence, the approximation of \( p_\emptyset \) should take the variable duration of sensed slots into account. We use the approach \( p_\emptyset \approx (p'_t \sigma)/(p'_t \sigma + (1 - p'_t)\Gamma tx) \). To estimate of \( p_\emptyset \) we periodically count the number of frames waiting for transmission. Let \( q \) be the sum of the samples expressing the number of frames waiting for transmission, which are sampled in the last \( B \) periods. \( p_\emptyset \) is given by \( 1 - q/(BK) \), where \( K \) denotes the MAC buffer size. The samples used in the sum \( q \) are periodically sampled using the frequency \( 1/(p'_t \sigma + (1 - p'_t)) \), which is abreast of the approach considered in [6], where the conditional arrival probabilities for busy and idle slots are considered to be proportional to the lengths of those slots. The missing parameter to compute (11) is the number of slots \( l \) expressed in (10). We approximate \( l \) as \( (W_0 - 1)/2 \), which correctly models the case when at least one frame is backlogged when the post backoff of the previous transmission starts.

### IV. EXPERIMENTAL RESULTS

Fig. 2 presents the results obtained through simulation of a network with 10 nodes. The simulations were performed with the network simulator ns-2 [12] using the 802.11b direct-sequence spread spectrum protocol and considering an

\(^1\) in \( \Gamma tx \), we assume that the duration of the acknowledge timeout is equal to the time needed to receive the acknowledge frame when the transmission succeeds.
TABLE I
IEEE 802.11b DSS PARAMETERS AND ADDITIONAL PARAMETERS USED.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIFS, 10 μs</td>
<td></td>
</tr>
<tr>
<td>DIFS, 30 μs</td>
<td></td>
</tr>
<tr>
<td>EIFS, 364 μs</td>
<td></td>
</tr>
<tr>
<td>ACK, 304 μs</td>
<td></td>
</tr>
<tr>
<td>Slot Time (μs)</td>
<td>20 μs</td>
</tr>
<tr>
<td>Propagation Delay (μs)</td>
<td>1 μs</td>
</tr>
<tr>
<td>Backoff Stages (m)</td>
<td>6</td>
</tr>
<tr>
<td>ACK Timeout</td>
<td>304 μs</td>
</tr>
<tr>
<td>Buffer size (K) [frames]</td>
<td>20</td>
</tr>
<tr>
<td>Frame Payload</td>
<td>2000 bytes</td>
</tr>
<tr>
<td>Sampling window size (B)</td>
<td>6000</td>
</tr>
</tbody>
</table>

ideal channel with a two ray ground propagation model. The simulation parameters are described in Table I. Fixed length frames containing 2000 bytes of payload are transmitted by 10 nodes within range of each other. The figure reports the mean of probabilities computed by one of the nodes (node j). We plot the mean of probabilities \(1 - p_i = p_s + p_c\) and \(p_c\) for different network loads. The network traffic load presented in the x axis is aggregate load, namely the sum of the average number of frames exponentially generated by each one of the 10 nodes. The same frame generation rate is used for all nodes. In other words, the nodes are homogeneous traffic sources (we designate this simulation scenario as **scenario A**). The results clearly demonstrate a non-saturated zone (when the total number of generated frames is between 0 and approximately 420 frames per second) and a saturated zone where the probability of sensing busy slots starts to become constant (for the circumstances where more than 420 frames per second are generated).

Fig. 3 presents the results obtained with the same simulation scenario described for Fig. 2 but now, one of the nodes (we will call it node 1) is exponentially generating 75% of network’s aggregated load, while its neighbors are homogeneously generating the remaining 25% (we designate this scenario as **scenario B**). When compared to Fig. 2, it is shown that both the collision probability \(p_c\) and the probability of sensing busy slots \(1 - p_i = p_s + p_c\) decrease for the heterogeneous scenario B. This is due to the decrease of the probability that two or more transmissions collide when heterogeneous traffic sources are used.

Fig. 4 presents the mean of the service times estimated by a node that is homogeneous, as in scenario A. The mean of estimated times in a given node is compared with the sensed service times (we designate it "Real"). The results depict the long term estimator accuracy and demonstrate a region where the estimator accuracy decreases, which occurs close to the transition from non-saturation to saturation (near to 400 frames/sec.). For the heterogeneous traffic scenario B, we show the mean service times estimated/sensed by the highest loaded node and by one of the 9 less loaded nodes in Figs 5 and 6, respectively. The service time is higher for the less loaded node, because their contention period is higher due to...
the higher channel occupation caused by the highest loaded node. The results still depict the trend related with a smooth decrease of the estimator accuracy near the transition between the non-saturated zone to the saturated one. In Fig. 7 we plot the mean of the probabilities \( p_0 \) (probability of having the queue empty) computed by the highest loaded node (node 1) and by one of the 9 less loaded nodes (node 5). The most loaded node has lower values of \( p_0 \) as it senses a higher ratio between the frame’s generation rate and the frame’s service rate.

Fig. 8 shows the results for the estimation error when two different values of \( B \) (the channel slot’s sampling window) are used. The error is shown in percentage and is normalized by the mean service time sensed by each node. The results were obtained for the loading value of 500 frames/sec with the same scenario described for the Fig. 5. Our purpose here is to analyze the estimator’s error dynamics. As can be seen, the error is lower than 1% after 2 seconds of simulated time for the two distinct sampling windows used, and it never grows more than 7% from the instant when the sampling window is completely buffered.

V. CONCLUSIONS

This work presents a long term estimation technique for the IEEE 802.11 DCF service time that relies only on local knowledge available at each node. From the simulation results we observe the better performance of the IEEE 802.11 protocol when there are heterogeneous traffic sources.

Although very simple, this technique generates accurate estimates without requiring high computational power. If traffic sources are elastic and rapidly changing its traffic generation pattern, this estimator is not appropriate because it does not take into account the variance or statistical moments of higher order. Future work will explore the opportunities of using more sophisticated techniques based on estimation theory, to estimate the service time for this kind of traffic.

REFERENCES


